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EQUILIBRIUM CHARGE STATES OF $^{16}$O
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Equilibrium Charge States of $^{16}\text{O}$
Ions and a Study of the $^{12}\text{C}(\text{He}^3,\text{n})^{14}\text{O}$
Reaction by Pulsed-Beam Time-of-Flight
Techniques

by

Davy Lee Bernard

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PART I. Equilibrium Charge States of Oxygen 16 Ions
A. INTRODUCTION

The average charge carried by an ion moving through matter depends upon the state (gaseous or solid) of the absorbing material, the ion's velocity, and the atomic number \( z \) of the ion. For ion velocities much greater than the orbital velocity of the electrons in a given electron shell of the ion, the shell is fully stripped of its electrons. For velocities less than or equal to the orbital velocity of the electrons in a given shell, the shell is only partially stripped, capturing and losing electrons as the ion goes through matter. Therefore, a beam of ions, traversing a certain amount of homogeneous material, reaches an equilibrium charge distribution characteristic of the ion's atomic number, the ion's velocity and the state of the material.

Experimental information on the equilibrium charge distributions of heavy ions is important for the theoretical understanding of the stopping powers of heavy ions. The knowledge of the equilibrium charge distribution is also quite useful in many experimental situations. Two examples are (a) the evaluation of the performance of tandem Van de Graaffs in producing beams of heavy ions by the stripping of the heavy ions in the terminal and (b) the deduction of the absolute intensity of a heavy ion beam in a scattering chamber by the measurement of the current in a Faraday cup after the heavy ion beam has passed through a foil.

In recent years a considerable amount of experimental work has been done to determine equilibrium charge states of oxygen ions emerging
from solid targets. Northcliffe\textsuperscript{1)} has measured the equilibrium charge distribution of $^{16}$O ions emerging from aluminum foils in the energy range of 16-120 Mev. Heckman \textit{et al.}\textsuperscript{2)} have measured the equilibrium charge distribution of $^{16}$O ions emerging from zapon foils in about the same energy range. At lower energies, Stephens \textit{et al.}\textsuperscript{3)} and Nikolaev \textit{et al.}\textsuperscript{4)} have measured charge state distributions of $^{16}$O ions emerging from zapon foils.

In the present investigation, the charge fractions of $^{16}$O ions emerging from gold and nickel foils in the $^{16}O^{+8}$, $^{16}O^{+7}$, $^{16}O^{+6}$, $^{16}O^{+5}$, and $^{16}O^{+4}$ ionization states were measured as a function of the ion velocity for the emergent energy range of 10-25 Mev. The design of the apparatus with which rapid, accurate accumulation of data could be possible is described. The root-mean-square of the charge of the ion is presented as a function of ion velocity for the two target materials used. The results are compared with other data for possible systematic behavior of the degree of ionization of $^{16}$O ions as a function of the atomic number of the stopping material. A test of Dimitriev's\textsuperscript{8)} probability theory of charge exchange processes is also discussed.
B. EXPERIMENTAL METHOD

1. Description of the Apparatus.

The apparatus was arranged as illustrated in the schematic diagram of Figure I-1. A small brass scattering chamber 7 inches in diameter and 4 3/4 inches high was built to contain the self-supporting stripping foils. Provisions were made on the lid of the chamber to mount a solid state detector, with appropriate collimating and anti-scattering slits, to function as a monitor. The lid was made to rotate so that the monitor detector could be positioned at any angle with respect to the beam direction within an angular range of 30° to 150°. Beam collimating slits were made of two tantalum discs with 1/8 inch circular apertures. The two discs, placed in the beam entrance port of the chamber, were separated by 3 inches.

A 3 inch diameter, 1/8 inch thick, brass disc was installed on a shaft extending through the bottom of the chamber. Four aluminum target holders were mounted on the periphery of the disc. The disc could be rotated externally so that any one of four targets could be selected.

At 30° from the beam direction, the coulomb scattered beam of ions was allowed to enter the magnetic spectrometer assembly. A set of adjustable tantalum slits were located 12 inches from the target and just before the magnet. The slit aperture size was variable vertically and horizontally and defined the acceptance angle of the magnet.
Figure I-1. A schematic diagram of the arrangement of the apparatus.
The magnet was originally designed as a 20° bending magnet. However, in order to be able to bend the ion beams within the momentum range available in this experiment, the magnet was used to deflect ions at an angle of 15°. A brass wave guide of inner cross sectional dimensions of 1 1/4 inches by 1/2 inch and with 1/16 inch thick walls was used as part of the deflected ion beam tube between the acceptance slits of the magnet and the analyzing detectors after the magnet. The wave guide just fitted into the 2 centimeter gap of the 15° analyzing magnet and was constructed into a 15° "Y". The straight through branch was provided with a diffused junction silicon detector for purposes of aligning the magnetic spectrometer such that points defined by the target, the center of the acceptance slits, the center of the magnetic field of the magnet, and the detector were collinear. Another solid state detector was placed at the end of the 15° branch of the "Y" for ion momentum analysis and ionization state identification purposes.

Sets of collimating and anti-scattering slits were arranged before the 15° analyzing detector. The detector defining slit was a 5 mil thick tantalum disc with a 1/16 inch circular hole. At 1 1/4 inch from the detector was a similar disc with a 1/8 inch hole comprising the anti-scattering slit. At 9 inches from the detector was a second collimating slit of rectangular dimensions 5/16 inch by 5/16 inch. The dimension and position of the acceptance slit, collimating slits, and anti-scattering slit were calculated such that the solid angle of \(9 \times 10^{-4}\) steradian defined by these slits defined a cone which just accepted the target area and minimized in-scattering of the ions from the walls of the scattered ion beam tube.
The current source for the analyzing magnet was provided by a 3 kilowatt D. C. generator whose field coils were activated by a low voltage, high current power supply. Regulation of the magnet current was made by feeding a voltage signal from a standard .01 ohm resistor located in the magnet current line into a Leeds and Northrup type K-2 potentiometer. The output voltage of the generator field coil power supply was varied by adjusting its plate voltage by means of a continuous voltage divider. Thus, for each magnet current setting, the slide wire of the potentiometer was adjusted until the potentiometer galvanometer showed zero deflection. Any small variation from the galvanometer zero was easily corrected by adjusting the voltage divider in the plate circuit of the D. C. generator field coil power supply.

With this technique of monitoring the D. C. generator output current, a check was made on the maximum variation of current for any given period of time. The maximum variation was never more than 10% of the current interval used to vary the field of the analyzing magnet. Since current intervals of 0.1 ampere were employed, the uncertainty of any analyzing magnet current increment was not more than 0.01 ampere. The arrangement of the magnet current controlling electronics is shown in Figure I-2.
Figure I-2. Schematic diagram of the ion analyzing magnet current controlling electronics. $R_o$ is the internal resistance of the D.C. generator, $R_L$ is the analyzing magnet coil resistance, and $R_s$ is the 0.01 ohm standard resistor.
2. Calibration Techniques.

Before incorporating the analyzing magnet with the rest of the apparatus, a test was made to determine the value of the magnetic flux density at which saturation began to occur. This test was made using a small coil of fine wire attached in series to a wall galvanometer. This method of measuring magnetic flux density is known in more familiar terms as the "snatching coil" method. The coil and galvanometer assembly was precalibrated such that each galvanometer deflection corresponded to a unique value of magnetic flux density. Figure I-3 shows a plot of the magnetic flux density of the analyzing magnet as a function of the magnet current. This graph clearly shows saturation occurring at a magnetic flux density of about 10.7 kilogauss.

A test was also made to check the magnetic field homogeneity of the analyzing magnet. This was done with a Hall-Effect probe. The probe element on hand was accurate for magnetic fields up to about 600 gauss. The magnetic field of the magnet was set to about 400 gauss and the position of the probe located between the pole faces was varied such that the magnetic field read from the gaussmeter could be compared for about 20 different probe locations. No appreciable change of magnetic field was observed for probe positions within the volume of the gap between the pole pieces. It was then assumed that the field homogeneity remained constant for all magnetic field values.

Once the analyzing magnet was incorporated with the rest of the apparatus a more accurate measure of the magnetic flux density as a function of magnet current was done while in actual use on the tandem
Figure I-3. A graph representing the magnetic flux density as a function of the current of the analyzing magnet.
Van de Graaff. A proton beam, energetically analyzed by the accelerator's 90° magnet, the magnetic field of which was determined by an NMR probe, was incident on a thin gold foil located in the scattering chamber. At 30° from the incident direction the elastically scattered protons were accepted into the ion analyzing magnet via the tantalum acceptance slits of the magnet. Before the magnetic field was applied, the counting rate of the detector at the end of the 0° deflection branch of the "Y" was maximized by adjusting the relative positions of the scattering chamber, acceptance slit box, and solid state detector. This assured maximum collinearity of the points defined by the target, acceptance slit, and the detector. The proton beam was then deflected into the 15° branch of the "Y" and detected by another solid state detector.

Proton energies of 5, 7, and 9 Mev were found sufficient for obtaining a curve of magnetic rigidity (Bρ) as a function of the beam energy. At each proton energy, the magnet current was varied in steps of 0.1 ampere until the counting rate in the 15° detector had gone over a maximum. These proton spectra were recorded by a 400 channel analyzer. The ratio of the yield of each proton group was plotted as a function of magnetic rigidity (Bρ). The Bρ position of the peak of the proton distribution for a given incident proton beam energy was plotted as a function of the square root of the beam energy in Mev. The results of these measurements are shown in Figure I-4. Calibration of the magnetic spectrometer with a proton beam scattered from a thin gold foil was made before and after each set run to enable
Figure 1-4.
The graphs represent the analyzing magnet calibration procedures. The three peaks represent 5, 7, and 9 MeV proton beams analyzed by the magnet. The $B^0$ position of the maximum of each peak is then plotted as a function of $(E_p)^{1/2}$ and is illustrated by the straight line.
the observation of any change in the alignment of the spectrometer resulting in a possible change of the radius of curvature of the analyzing magnet.
3. The Oxygen Beam.

Special precautions had to be taken for operating the duoplasmatron ion source of the tandem Van de Graaff accelerator in order to have optimum conditions for obtaining an oxygen beam from the source. 5) The usual way of operating the source when running an oxygen beam was to feed a mixture of source gas consisting of about 400 microns of pressure of hydrogen and 10 to 50 microns of oxygen. A pure quantity of oxygen was found to be detrimental to the platinum filament and did not yield much more oxygen beam than with the mixture. The function of the 400 microns of pressure of hydrogen was mainly to strike and sustain the arc current between the magnet probe and source aperture (button) of the duoplasmatron ion source. Furthermore, it was found that if the source filament was immersed in a solution of barium oxide, allowed to dry for about an hour, and remounted, the arc could be struck and sustained without introducing any source gas for about 12 hours. All other features of the ion source were operated in the usual manner as for obtaining beams of protons or deuterons. The 20° ion bending magnet between the source and entrance port of the accelerator was operated at about 400 milliamperes of current, depending, of course, on the ion extraction voltage which ranged between 35 to 40 kilovolts.

The oxygen ions extracted by the extraction voltage are positive ions, presumably in the +1 ionization state. After being accelerated by the -40 kilovolt extraction potential, the positive oxygen ions enter an exchange canal where hydrogen gas is used as the exchange gas
at a pressure of about $4 \times 10^{-5}$ centimeter of mercury. There the positive oxygen ions are transferred to the $-1$ ionization state and accelerated by an additional 40 kilovolts. After being analyzed by the $20^\circ$ magnet, the $O^-$ ions enter the accelerator. The $O^-$ ions are then partially stripped of their electrons in the electron stripping canal located in the high voltage terminal of the accelerator. The oxygen ions emerging from the stripping canal are in one of the four predominant charge states of $O^{+3}$, $O^{+4}$, $O^{+5}$, and $O^{+6}$, the most intense of which was the $O^{+4}$ state. The $90^\circ$ analyzing magnet was then used to select the desired beam of oxygen ions. The beam of ions used in this experiment was in the $O^{+4}$ ionization state, with the exception of a small amount of qualitative data which was taken with the $O^{+5}$ beam.

The beam of $O^{+4}$ ions incident in the scattering chamber ranged in energy from 15 to 30 Mev. Self-supporting targets of gold and natural nickel of thickness 870 $\mu$gm/cm$^2$ and 560 $\mu$gm/cm$^2$, respectively, were used as the beam absorbing material. The bombarding energy was varied in steps of 2.5 Mev. At each incident energy setting, the ion analyzing magnet current was varied and the intensity of all the charge states emerging from the target were measured except the very low intensity beams of low charge states which were outside the analyzing power of the magnet.
C. DISCUSSION OF RESULTS

A foil $10^{-5}$ centimeter thick, as in the case of the gold and nickel foils used in the present experiment, consists of about 500 layers of atoms. An ion traversing such a foil will undergo a large number of collisions with target electrons since the atoms in a solid are closely packed. When the ion emerges from the foil, a state of equilibrium has been reached by the ion in the process of charge exchange. A detailed description of the capture and loss of electrons by a heavy ion during its passage through a decelerating medium is difficult.

Several attempts have been made at devising a suitable explanation of the charge exchange process. Bohr\textsuperscript{6}) assumed in his calculations of energy range relationships for fission fragments that at each point of the path, the ion retains all of its electrons whose orbital velocities are greater than the translational velocity of the ion. Lamb\textsuperscript{7}) made similar calculations based on the assumption that the electrons within the stopping material are free. This assumption seems to lead to a crude interpolation of data except at high ion velocities. Another theory, based on Lamb's assumption, is that of Dimitriev\textsuperscript{8}) in which the occupational probability for each electronic state is represented by a function of $v/v_i$, where $v$ is the velocity of the ion and $v_i$, the velocity of the $i^{th}$ orbital electron of the ion. Using Bohr's approach, Knipp and Teller\textsuperscript{9}) have used the Thomas-Fermi statistical model of the atom to calculate the velocity of the most loosely bound electron within the ion as a
function of the ionic charge. In particular, they have calculated \( i/z \)
as a function of \( v_e/(z)^{2/3} \), where \( i \) is the number of electrons needed
to neutralize the ion and \( v_e \) is the velocity of the most loosely bound
electron within the ion. The data of the present experiment has been
analyzed within the framework of the calculations of Knipp and Teller.

Figures I-5 through I-17 show histograms of the charge state
distributions of oxygen ions emerging from gold and nickel targets.
The distributions illustrated were taken at every 2.50 Mev energy
step in the bombarding energy range of 15.00 to 30.00 Mev in the case
of gold as the target and 15.00 to 27.50 Mev in the case of nickel as
the target. The corresponding emergent ion velocity range is
11.4 \( \times 10^8 \) centimeters per second to 17.6 \( \times 10^8 \) centimeters per second
in the case of the gold target and 11.6 \( \times 10^8 \) centimeters per second
to 16.9 \( \times 10^8 \) centimeters per second in the case of the nickel target.
The ion energy loss in the target was calculated from the shift of
the positions of the charge state peaks when compared to the expected
positions at the given incident bombarding energy.

The ion energy loss in the gold target ranged from 4.3 Mev at
an incident bombarding energy of 15.00 Mev to 3.5 Mev at incident
energy of 30.00 Mev. In the case of the nickel target, the energy
loss ranged from 4.0 Mev at 15.00 Mev incident bombarding energy to
3.4 Mev at an incident energy of 27.50 Mev. An average energy reso-
lution of 12 percent for the analyzing system was calculated from the
full width at half maximum of the charge state peaks. The energy
resolution was calculated for each peak and then averaged. An increase
Figures I-5 - I-11. Charge state distributions for an $O^{4+}$ beam incident on a gold foil of thickness 870 $\mu$gm/cm$^2$. A charge distribution spectrum was taken at each 2.50 Mev incident energy step for the bombarding energy range of 15.00 to 30.00 Mev. Note the broadening of the low charge state peaks when compared to the high charge state peaks.

Fig. I-5.  

Fig. I-6.  

Fig. I-7.  

Fig. I-8.
$^{14}O + Au$

$E_{inc.} = 15.00 \text{ MeV}$
Emergent ion Velocity = $11.38 \times 10^8 \text{ cm/sec}$

$E_{inc.} = 17.48 \text{ MeV}$
Emergent ion Velocity = $12.60 \times 10^8 \text{ cm/sec}$

$E_{inc.} = 20.00 \text{ MeV}$
Emergent ion Velocity = $13.75 \times 10^8 \text{ cm/sec}$

$E_{inc.} = 22.50 \text{ MeV}$
Emergent ion Velocity = $14.62 \times 10^8 \text{ cm/sec}$
Fig. I-9.  

Fig. I-10.

Fig. I-11.  

Fig. I-12. (Nickel)
Figures I-12 - I-17. Charge state distributions for an O$^{+4}$ beam incident on a natural nickel foil of thickness 560 µgm/cm$^2$. A charge distribution spectrum was taken at each 2.50 Mev incident energy step for the bombarding energy range of 15.00 to 27.50 Mev. Note the broadening of the low charge state peaks when compared to the high charge state peaks.

Fig. I-13.  Fig. I-14.

Fig. I-15.  Fig. I-16.

Fig. I-17.
$O^{+4} + Ni$

$E_{\text{inc.}} = 27.50 \text{ MeV}$

Emergent Ion Velocity =

$16.87 \times 10^8 \text{ cm/sec}$
of the intensity of high charge states with increasing ion velocity is clear from these spectra. The histograms also show a broadening of the charge state peaks as $B \rho$ increases. This is characteristic of any magnetic spectrometer where the measurements are plotted as yield versus the magnetic flux density of the magnet. If, as in the present situation, the spectrometer has a constant energy resolution throughout the energy range investigated, then the relation

$$\frac{\Delta E}{E} = 2 \frac{\Delta B}{B}$$

holds where $E$ is the kinetic energy of the ions analyzed by the spectrometer and $B$ is the magnetic flux density of the magnet. Thus, while varying the magnetic field of the spectrometer, $\Delta B$ varies by the same proportion.

Since the next step in the analysis of the data shown in Figures I-5 through I-17 was to calculate the relative yields of the ionization states, a correction to the data had to be made. If the yields under each charge state peak are integrated, more yield of the low ionization states is obtained than is actually the case and any calculations leading toward an evaluation of the average charge of the ions emerging from the foil would result in obtaining a smaller value for the average charge than should actually be the case. The correction to be applied should effectively make each spectrometer scanning interval correspond to equal ion momentum intervals. The derivation of the correction factor applied to the yield of each ionization state is presented in Appendix 1. The results of such calculations are tabulated there.
Once the correction to the charge state distribution was made, the charge state fractions, $\bar{\Phi}_Z$, at each emergent ion velocity were calculated for the oxygen ions emerging from the gold and nickel foils. This calculation was done by dividing the yield of each charge state at a given emergent ion velocity by the integrated yields of all the states at that velocity. The results of such calculations are shown in Table I-1. The errors indicated in the $\bar{\Phi}_Z$'s account only for the statistical fluctuations of the counting rate recorded by the solid state detectors since that was the only significant contribution to the error. Another possible error contribution could be that due to ion analyzing magnet current instabilities. But, as mentioned above, the instability was a maximum of 10 percent of the magnet current increments taken. Thus, the error in the magnet current setting was less than 1 percent for low current values and decreased for the high current values used. This would tend to increase the charge state peaks by a very small fraction, thus having only a small effect on the vertical error bars on the $\bar{\Phi}_Z$'s. Also, incident beam defining slits before the scattering chamber provided a small beam spot of about 3 millimeters in diameter, always located at the same position on the target, so that errors due to non-uniformity of foil thickness were negligible. Finally, the incident ion beam energy uncertainty is less than 1 percent, and this effect contributes a negligible amount to the error bars placed on the $\bar{\Phi}_Z$'s.

The charge state fractions, $\bar{\Phi}_Z$, for oxygen ions emerging from a gold foil 870 $\mu$gm/cm$^2$ thick are plotted in Figure I-18 as a function
TABLE I-1.
Charge state fractions ($\Phi_2$) calculated from the charge state (Z) distributions. The errors
($\Delta \Phi_2$) are due to statistical fluctuations of the counting rate of the solid state detectors.

<table>
<thead>
<tr>
<th>Target</th>
<th>Ion Velocity V($10^{-8}$)cm/sec.</th>
<th>$\Phi_8$</th>
<th>$\Delta \Phi_8$</th>
<th>$\Phi_7$</th>
<th>$\Delta \Phi_7$</th>
<th>$\Phi_6$</th>
<th>$\Delta \Phi_6$</th>
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<td>Gold</td>
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<td>0.004</td>
<td>0.151</td>
<td>0.017</td>
<td>0.564</td>
<td>0.042</td>
<td>0.248</td>
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<td></td>
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<td>0.002</td>
<td>0.002</td>
</tr>
</tbody>
</table>
of the emergent ion velocity in centimeters per second and also as a function of emergent ion energy in units of Mev per nucleon of the bombarding particle. The horizontal error bar represents the 12 percent energy resolution of the entire ion detection system which includes (a) incident beam energy spread, (b) straggling of the ions in the target material, and (c) magnetic spectrometer energy resolution which includes small effects due to magnet current instabilities. The most predominant charge state group of ions in the energy range of 0.63 Mev per nucleon to 1.56 Mev per nucleon is the $O^{+6}$ charge state. The $O^{+4}$ charge state, the lowest state seen in this experiment, rapidly decreased in intensity until it became undetectable at about 1.2 Mev per nucleon.

It would be advantageous to display charge distribution data in another way. If it is assumed that charge exchange in an ion occurs primarily by capture or loss of a single electron; that is if one neglects multiple charge exchange, then equilibrium conditions yield the relationship

$$\frac{\sigma_x(i)}{\sigma_c(i+1)} = \frac{\Phi_{i+1}}{\Phi_i}$$

where $\sigma_x(i)$ and $\sigma_c(i+1)$ are the single electron loss and capture cross sections for ions with charge $i$ and $i+1$, respectively. Thus loss to capture cross section ratios are given by the equilibrium charge fraction ratios. Furthermore, Bohr\textsuperscript{12} predicted theoretically that $\sigma_x/\sigma_c$ for this situation should be a constant power of the ion velocity so that a plot of $\log(\Phi_{i+1}/\Phi_i)$ versus $\log(v)$ should be
approximately a straight line. Unfortunately, however, the data of
the present experiment do not lend themselves to such analysis. From
Figure I-18 it is clear that only in the energy region around 1.5 Mev
per nucleon, is the cross section for the capture or loss of one
electron predominant. Therefore, the only explicit relationship of
loss and capture cross sections which hold for this data is,

\[
\frac{\sigma_{6,7}}{\sigma_{7,6}} \approx 1
\]

at 1.5 Mev per nucleon.

Figure I-19 shows the charge fractions of $^{16}\text{O}$ ions emerging from
a nickel foil 560 \(\mu\text{gm/cm}^2\) thick. The fractions are plotted as a
function of emergent ion velocity and energy per nucleon. These
graphs exhibit the fact that no appreciable difference exists between
charge state distributions of oxygen ions emerging from gold and
nickel foils.
Figure I-18. Charge state fractions for an $O^{+4}$ beam incident on a gold foil of thickness 870 $\mu$gm/cm$^2$. The fractions are plotted as a function of emergent ion energy per nucleon (Mev/nucleon). The vertical error bars are due mainly to statistical fluctuations of the counting rate. The horizontal error bar is the 12 percent energy resolution of the spectrometer.

Figure I-19. Charge state fractions for an $O^{+4}$ beam incident on a natural nickel foil of thickness 560 $\mu$gm/cm$^2$. The fractions are plotted as a function of emergent ion velocity in centimeters per second and as a function of emergent ion energy per nucleon (Mev/nucleon). The vertical error bars are due mainly to statistical fluctuations of the counting rate. The horizontal error bar is the 12 percent energy resolution of the spectrometer.
D. THEORY

An ion moving through matter with a velocity about equal to the orbital velocity of some of its own electrons will experience a fluctuating net charge as electrons are captured by or lost to the material as the ion collides with the atoms. Thus if a monoenergetic beam of identical ions is incident on matter, the result will be a characteristic distribution of charge states of the ions. If \( \Phi_Z \) is the fractional number of ions with charge \( Z \), \( Z \) being any integer \( 0 \leq Z \leq Z \), where \( Z \) is the atomic number of the ion, then the characteristic distribution may be represented by the set of ratios \( \Phi_Z, \Phi_{Z-1}, \ldots, \Phi_0 \).

The instantaneous stopping power for the case of an ion moving through matter varies approximately as \( Z^3 \). Furthermore, the ion spends the fraction \( \Phi_Z \) of its time in the charge state \( Z \). Thus the average stopping power is approximately proportional to the mean squared charge of the ion, written as

\[
\overline{Z^2} = \sum_{Z=1}^{Z} \Phi_Z (Z)^2
\]

or

\[
\overline{Z_{rms}} = \sqrt{\overline{Z^2}} = \left[ \sum_{Z=1}^{Z} \Phi_Z (Z)^2 \right]^{1/2}
\]

where \( \overline{Z_{rms}} \) is the root mean square value of the charge of the ion.

The first theoretical works describing charge exchange phenomena of heavy ions arose from attempts to describe the range of fission fragments in matter. Bohr calculated an estimate of the charge of a fission fragment on the assumption that an electron was either
permanently lost by a fission fragment depending on whether the fragment's velocity was much less than or much greater than the electron's orbital velocity.

Lamb\textsuperscript{7}) postulated a similar model for charge exchange of fission fragments. His assumptions were that (a) for any velocity of a fission fragment, there will be an associated average charge, about whose value the actual charge fluctuates very slightly, and (b) the fragment will be stripped down until the ionization potential of the next stage of ionization is greater than the kinetic energy of the electrons bombarding the fragment with a velocity $v$. This last assumption essentially neglects the binding energy of the electrons in the target material.

Knipp and Teller\textsuperscript{9}) used Bohn's approach and applied the Thomas-Fermi statistical model of the atom to obtain the orbital electron velocities of an ion as a function of the ionization of the ion.

Brunings, Knipp and Teller\textsuperscript{13}) calculated the orbital electron velocities of an ion for the cases, (a) assuming $v_e$ is the velocity of the energetically most easily removed electron from the ion, and (b) assuming $v_e$ is the velocity of the outermost electron of the ion. The results of these two assumptions do not differ much from the results of Knipp and Teller's calculations which agree well with experimental data.\textsuperscript{10}) Therefore, the data of the present experiment has been analyzed within the framework of these calculations.

A brief description of some charge exchange calculations\textsuperscript{9}) will be given here, while the detailed derivation of the expressions is presented in Appendix 2.
An expression which describes the radial distribution of the electrons of an ion can be written as

\[ \frac{d\varphi}{dr} = \frac{32 \pi^2 r^2 \left[ 2m_e \Phi(n) \right]^{3/2} dr}{3 \lambda^3} \]

where \( n \) is the number of occupied electron states in the ion, \( r \) is the distance within the ion measured from the center of the ion, \( m \) is the electron mass, and \( \Phi(n) \) is the net potential which an electron would experience at a distance \( r \) from the center of the ion. The number of electrons whose energies are found in an infinitesimal potential energy range is given by

\[ \frac{d\varphi}{d\Phi} = \frac{4\pi^2 (2m_e)}{3 \lambda^3} \int_0^{r_o} r^2 dr \left[ 2m_e \Phi(n) \right]^{1/2} \]

where \( r_o \) is the radius of the ion where the electron density vanishes.

From this equation, one can obtain an expression for the orbital velocity of the electrons in an ion as a function of the degree of ionization of the ion, given by

\[ \frac{\mathcal{V}_e}{Z^{2/3}} = \left[ \left( \frac{1004}{9 \pi^2} \right)^{1/3} \frac{1}{I} \right]^{1/2} \left( \frac{Z_{\text{rms}}}{2} \right)^{1/2} \]

where \( Z_{\text{rms}} \) is the root-mean-square of the charge of the ion, \( Z \) is the atomic number of the ion and \( I \) is an integral whose value has been determined by Fermi\(^{14} \) and Miranda\(^{15} \). Thus, a plot of \( Z_{\text{rms}}/Z \) versus \( v_e/Z^{2/3} \) has a parabolic behavior for low values of \( Z_{\text{rms}}/Z \) and varies.
asymptotically for $Z_{\text{rms}}/Z$ approaching the value 1 and where $v_{e}/vZ^{2/3}$ increases rapidly.

Since there is a definite dependence of the charge exchange process on the ion velocity being comparable to the orbital velocity of the electrons of the ion, the data of the present experiment was plotted in terms of $Z_{\text{rms}}/Z$ versus $v/Z^{2/3}$, where $v$ is the velocity of the ion while moving through matter. The resulting graph is shown in Figure I-20. The other data shown has been replotted in terms of the parameters $Z_{\text{rms}}/Z$ and $v/Z^{2/3}$, where $Z_{\text{rms}}$ was calculated from the experimentally determined $\Phi_{Z}^{1}$'s according to the expression

$$Z_{\text{rms}} = \left[ \sum_{Z} \Phi_{Z}^{1}(Z) \right]^{1/2}.$$ 

Working on the assumption that the relative velocity $v_{e}/v$ contains crucial information on the charge exchange process, Dimitriev proposed that the probability for capture (or loss) of a given electron depends on the ion's velocity, $\beta = v/c$, and is independent of the capture or loss of other electrons by the ion. The equilibrium charge fractions at velocity $\beta$, could then be expressed in terms of a set of $N$ independent functions. $X(\beta)$ is the probability that the $n^{\text{th}}$ electron is absent from the ion. In the case of a four-electron system for an $0^{+4}$ ion the probabilities $X_{n}(\beta)$ are expressed by the following relationships.
Figure I-20. The root-mean-square of the charge on the ion was calculated from the charge fractions and plotted in the framework of the theory of Knipp and Teller\textsuperscript{9}). Other data, analyzed in the same manner, are also shown. The points on the abscissa labeled $L_2$, $L_1$, $K_2$ and $K_1$ correspond to values of $\frac{\mathcal{N}_e}{z^{2/3}}$ where $\mathcal{N}_e$ is the orbital electron velocity of the $L_2$, $L_1$, $K_2$ and $K_1$ electrons of the ion, respectively. These orbital electron velocities were calculated by equating the electron kinetic energy to the electron binding energy which is justified for the case of a pure Coulomb field.
\[ z_\mu = 1 - x_\mu, \quad \mu = 1, \ldots, 4. \]

\[ \Phi_9 = x_1 x_2 x_3 x_4 \]

\[ \Phi_7 = x_1 x_2 x_3 z_4 + x_1 x_2 z_3 x_4 + x_1 z_2 x_3 x_4 + z_1 x_2 x_3 x_4 \]

\[ \Phi_6 = x_1 x_2 z_3 z_4 + x_1 z_2 z_3 x_4 + z_1 x_2 z_3 x_4 + x_1 z_2 x_3 z_4 \]

\[ \Phi_5 = x_1 z_2 z_3 x_4 + z_1 z_2 z_3 x_4 + z_1 z_2 x_3 x_4 + z_1 z_2 z_4 x_4 \]

\[ \Phi_4 = z_1 z_2 z_3 z_4. \]

In these expressions, the \( \Phi_L \)'s are determined experimentally. The problem is then to solve for the independent \( x_\mu \)'s.

A computer program, employing least square fits and searching subroutines, was written to solve for the independent \( x_\mu \)'s. The results are plotted in Figure I-21 in the case of the gold foil and Figure I-22 in the case of the nickel foil. One of the original postulates in Dimitriev's proposal is that the \( x_\mu (\beta) \) functions should be smoothly varying functions of the velocity \( v \) of the ion. The graphs of Figures I-21 and I-22 show the smooth behavior for the functions \( x_4 \) and \( x_3 \) which are assumed to be the functions describing the behavior of the L electrons in the \( O^{+4} \) ion. The assumption that \( x_4 \) and \( x_3 \) are the probability functions of the L electrons is based on the fact that the L electrons have higher probabilities of being stripped from the ion than the K electrons in the bombarding energy range reported here. No identification can be made as to which L electron is described by either \( x_4 \) or \( x_3 \). From the same reasoning used to identify the L shell...
Figure I-21. Charge exchange probabilities, calculated from Dimitriev's theory 8) of charge exchange phenomena, are shown as a function of emergent ion energy in Mev using the gold foil. Note the smooth variation of the probability functions only for the L electrons of the O$^{+4}$ ion. The error bars placed on the $X_i$'s correspond to a maximum error of ±10 percent due to the uncertainty in the measurement of the $\Phi_Z$'s.

Figure I-22. Charge exchange probabilities, calculated from Dimitriev's theory 8) of charge exchange phenomena, are shown as a function of emergent ion energy in Mev using a natural nickel foil. Note the smooth variation of the probability functions only for the L electrons of the O$^{+4}$ ion. The error bars placed on the $X_i$'s correspond to a maximum error of ±10 percent due to the uncertainty in the measurement of the $\Phi_Z$'s.
probability functions, \( X_2 \) and \( X_1 \) are assumed to be the probabilities for stripping the K electrons of the \( O^{+4} \) ion. These probabilities show a fluctuating behavior with an increase in bombarding energy.

The error bars placed on the \( X_1 \)'s correspond to a maximum error of 10 percent due to the uncertainty in the measurement of the \( \Phi_z \) 's. This theory of charge exchange appears to hold only at higher energies when applied to heavy ions--in the 100 Mev range of ion energies where K electron capture and loss processes are predominant. The theory holds quite well for Heckman's data\(^2\) with carbon, oxygen and neon ions moving through zapon foils in the bombarding energy range of 1.6 to 10.5 Mev per nucleon.
E. CONCLUSION

The following conclusions have been drawn from this study of charge exchange of oxygen ions moving through foils of gold and nickel. There is no indication of a difference between the charge state distributions using a gold foil and those obtained using a nickel foil in the emergent ion energy range of 0.63 Mev per nucleon to 1.56 Mev per nucleon. Furthermore, the degree of ionization of oxygen ions moving through gold and nickel foils in this energy range appears to be no different than that measured with aluminum and zapon foils within an experimental error of not more than 1 percent. The absence of effects due to the atomic number of the target material for the ion velocity range investigated indicates that from the point of view of the electrons in the target foils, the kinetic energy with which they bombard the incoming ion is much larger than their binding energies. The electrons of target materials ranging in weight from zapon to gold behave, with respect to the bombarding ion, as free particles. The root-mean-square charge of the ions varied from 5.62 at 0.63 Mev per nucleon to 6.56 at 1.56 Mev per nucleon.

The data of this experiment and other data were analyzed in the framework of the theory for charge exchange processes of Knipp, et al.\(^9\)), and agreed quite well in shape with this theory. A gratifying pattern of consistancy emerged in this manner of analysis.

Using Dimitriev's\(^8\)) probability considerations to describe charge exchange phenomena, the velocity dependent probability functions were calculated using experimentally determined charge fractions for the
emergent ion energy range of 0.63 to 1.56 Mev per nucleon. The prediction of smoothly varying probability expressions as a function of ion velocity seems to be satisfied only for the probabilities \( X_3 \) and \( X_4 \) which have been assigned to the L shell electrons of the four-electron system of the \( O^{+4} \) ion. The \( X_1 \) and \( X_2 \) probabilities, assigned to K shell electrons, exhibit fluctuating characteristics whose magnitudes are greater than the error bars. It is surmized that the conditions which should hold for agreement with this theory are (a) the translational velocity of the ion should be much greater than the orbital velocity of the electrons which the probability functions describe, and (b) the bombarding ion should contain only the K shell electrons if the behavior of the theory is to be compared with experiment over a large bombarding energy range. Condition (a) is certainly not satisfied in the present experiment if one recalls that the binding energy of the K shell electrons of oxygen is about 900 electron volts. This electron energy corresponds to an orbital electron velocity of \( 17.5 \times 10^8 \) centimeters per second, whereas the maximum ion velocity studied was \( 17.5 \times 10^8 \) centimeters per second. The \( O^{+4} \) atomic system certainly does not satisfy condition (b).
APPENDIX 1: YIELD CORRECTION APPLIED TO CHARGE STATE DISTRIBUTIONS

The derivation of the correction factor applied to the yield of the charge states was done in two different ways, both of which gave identical results and were based on the fact that each magnetic field increment used in the scanning procedure must correspond to equal ion momentum intervals.

The first method will be called the graphical method. Suppose there is a charge state peak of the charge state distribution data, say, the $O^{+6}$ state for an oxygen bombarding energy of 22.50 Mev on gold. Each unit on the $B\rho$ scale corresponds to 5 kilogauss-cm. The spectrometer scanning increment was 10 kilogauss-cm. Then the FWHM ion momentum interval for this charge state at the given bombarding energy is

$$\Delta_{Z} / n \times 10 \times Z \, e$$

where $n$ is the number of spectrometer scanning increments, and $Z$ designates the charge state of the ion. Let $\Delta_{Z}$ be the FWHM of the $Z$ charge state peak in units of $B\rho$. Thus, $\Delta_{Z} / n \times 10 \times Z \, e$, letting $e = 1$ for simplicity, is the number of $B\rho$ units per momentum units at FWHM. The correction factor by which the yield of a given charge state is multiplied is obtained from the ratio of $\Delta_{Z} / n \times 10 \times Z$ for the $O^{+8}$ state to that for the given state in the following table, letting $\Delta_{9} / n \times 10 \times 9$, $\Delta_{7} / n \times 10 \times 7$, etc.
TABLE 1-1

<table>
<thead>
<tr>
<th>Charge state</th>
<th>Ratio</th>
<th>Yield correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0+8</td>
<td>$e_8/e_8$</td>
<td>1.00</td>
</tr>
<tr>
<td>0+7</td>
<td>$e_8/e_7$</td>
<td>0.875</td>
</tr>
<tr>
<td>0+6</td>
<td>$e_8/e_6$</td>
<td>0.750</td>
</tr>
<tr>
<td>0+5</td>
<td>$e_8/e_5$</td>
<td>0.625</td>
</tr>
<tr>
<td>0+4</td>
<td>$e_8/e_4$</td>
<td>0.500</td>
</tr>
</tbody>
</table>

The second method used to derive the charge state yield correction factor makes use of the geometry of the spectrometer illustrated in Figure I-23. The magnetic field through which the ion moves exerts a force on the ion given by

$$ F = B f v = \frac{m v^2}{\rho} = m a $$

where $B$ is the magnetic flux density, $q$ is the charge of the ion, $m$ is the mass of the ion, $v$ is the velocity of the ion, $\rho$ is the radius of curvature of the magnet, and $a$ is the acceleration of the ion. After fringing fields are considered, one can write

$$ S_1 = \frac{1}{2} a t^2 $$

where $t$ is the time the ion takes to traverse the length of the magnetic field $d$. By similar triangles,

$$ S = \frac{x}{x_1} S_1 $$

where the dimensions $x, x_1, S$ and $S_1$ are illustrated in Figure I-1.
Figure I-23. This figure illustrates the geometry used to calculate the correction factors by which the yields of the charge states are multiplied.
Therefore,
\[ s = \frac{x}{2x_1} \cdot \frac{x}{v} \cdot \frac{B_k \nu}{m} \cdot t^2. \]

But \( t = \frac{d}{v} \). Thus,
\[ s = \frac{x}{2x_1} \cdot \frac{B_k \nu}{m} \cdot \frac{d^2}{v^2}. \]

or
\[ s = \frac{x}{2x_1} \cdot \frac{e^2}{\mu} \cdot (ZB), \]

where \( Z \) is the atomic number of the ion, and \( p \) is the momentum of the ion.

Thus,
\[ \frac{1}{s} \propto Z \cdot dB, \]

where \( dS \) is the ion beam spread at the detector and \( dB \) is the corresponding spread of magnetic field. Furthermore, \( dS/S \) is a measure of the energy resolution of the magnet, which is constant throughout the ion energy range analyzed. Thus, since \( S \) is held fixed for each charge state studied, \( dS \) must correspondingly be a constant. Then given any two charge states \( Z \) and \( Z' \) one can write the ratio
\[ \frac{dS}{dS} = 1 = \frac{Z \cdot dB_Z}{Z' \cdot dB_{Z'}}. \]

or
\[ \frac{dB_Z}{dB_{Z'}} = \frac{Z'}{Z}. \]
The final expression gives the relation between the spread of magnetic field which is required to analyze the two charge states $Z$ and $Z'$. Since this spread of magnetic field increases as lower charge states are analyzed, the above ratio can be used to correct for this effect. Also,

$$\frac{\Delta E}{E} = \frac{2 \Delta \mu}{p} = \frac{2 \Delta B}{B}$$

where $E$ is the kinetic energy of the ion and $p$ is its momentum. For any two charge states analyzed, one must have equal momentum intervals in order to determine the yield of the charge states in a distribution spectrum. Thus,

$$\Delta \mu_Z = \Delta \mu_{Z'}$$

so that

$$d B_Z = \frac{B_Z}{B_{Z'}} \, d B_{Z'} = \frac{Z}{Z'} \, d B_{Z'}$$

The yield correction factors derived in this manner are the same as shown above and are shown in Table 1-2.

<table>
<thead>
<tr>
<th>Charge state</th>
<th>Ratio</th>
<th>Yield correction</th>
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<tbody>
<tr>
<td>$0^{+8}$</td>
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<tr>
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<td>0.625</td>
</tr>
<tr>
<td>$0^{+4}$</td>
<td>$dB_8/dB_4$</td>
<td>0.500</td>
</tr>
</tbody>
</table>
APPENDIX 2: DERIVATION OF CHARGE EXCHANGE EXPRESSIONS

The following calculations are based on the Fermi-Thomas model\(^{17},^{18}\) of the atom. This model contains the following ideas. The space surrounding an atom can be divided up into a large number of "cells" such that the potential energy does not change appreciably throughout any given one. The energy states available to an electron within each cell will be equal to the potential energy for that cell plus varying amounts of kinetic energy appropriate to the size of the cell. There can be obtained in this manner many energy states to be occupied by the electrons of the atom each subject to the Pauli exclusion principle and to the condition that no states of positive total energy can be occupied. Positive energy states describe electrons not bound within the atom. Furthermore, since the lowest energy states are found in regions of low potential energy, one would expect to find more of these electron states near the nucleus. This is also a region of more bound states.

Thus, consider a small volume \(dV\) in an ion (or atom) at a distance \(r\) from the nucleus where the potential energy of an electron is \(-e\Phi(\Lambda)\). The electrons within such a small volume possess total energies similar to those of free particles, i.e., extending from \(0\) to \(-e\Phi(\Lambda)\). Furthermore, there is just one electron state within an atom per \(h^3\) units of phase space volume\(^{19}\), where \(h\) is Planck's constant. Therefore, if \(p\) is the momentum of an electron, the number of occupied states within the volume element \(dV\) is

\[
(1) \quad dN = \frac{2}{\pi \hbar^3} \pi p^2 \, dr
\]
where the factor 2 takes account of the two spin orientations of an electron. But
\[
\eta = \left[ 2m_e \Phi(n) \right]^{1/2}
\]
and
\[
d\tau = 4\pi r^2 \, dr
\]
Thus,
\[
(2) \quad d\Omega = \frac{\frac{32 \pi^2 r_n^2 \left[ 2m_e \Phi(n) \right]^3}{3 \hbar^3}}{\frac{18}{3 \hbar^3}} \, d\Omega
\]
This is a quasi-classical expression which describes the radial distribution of the electrons in terms of the potential distribution \( \Phi(n) \) within the ion.

Let equation (2) be written as
\[
(3) \quad \frac{d\Omega}{d\tau} = \frac{8 \pi \left[ 2m_e \Phi(n) \right]^{3/2}}{3 \hbar^3}
\]
The number of electrons whose potential energy lie in the infinitesimal range between \( e(\Phi - 4\Phi) \) and \( e\Phi \) is given by
\[
\frac{d^2 \Omega}{d\Phi \, d\tau} = \frac{4\pi (2m_e \left[ 2m_e \Phi(n) \right])^{1/2}}{\hbar^3}
\]
Thus,

\begin{equation}
\frac{dm}{d\xi} = \frac{(4\pi)^2 (2me)}{\xi^5} \int_0^{r_o} r^2 dr \left[ 2me \Phi(r) \right]^{1/2},
\end{equation}

where $r_o$ is the radius of the ion where the electron density vanishes.

The mean square velocity of the electrons in this range is obtained by multiplying the integrand of equation (4) by $1/m^2 (2me \Phi'(\xi))$, integrating, and dividing by equation (4):

\begin{equation}
\nu_e^2 = \frac{\int_0^{r_o} r^2 dr \left[ 2me \Phi(r) \right]^{1/2}}{m \int_0^{r_o} r^2 dr \left[ 2me \Phi(r) \right]^{1/2}}
\end{equation}

Introduce the dimensionless quantity $\nu_e' = \nu_e \hbar/e^2$ and make the following substitution of variables.

\begin{equation}
\phi = \frac{r \Phi(r)}{\xi e}
\end{equation}

\begin{equation}
x = \xi^{1/3} \left( 18/\pi m \right)^{1/3} r m e^2/\xi^2
\end{equation}

The (5) becomes,

\begin{equation}
\nu_e^2 / \xi^{4/3} = \left( \frac{1024}{9 \pi^2} \right)^{1/3} \int_0^{x_0} dx \int_0^{x_0} \phi^{3/2} \int_0^{x_0} dx \int_0^{x_0} \phi^{1/2},
\end{equation}

where the limit of integration is the value of $x$ for $r = r_o$. 
The integral

\[ I = \int_0^{x_0} dx' x'^{3/2} \Phi' \]

has been evaluated numerically and tabulated for various ions and degrees of ionization of ions \(^{14),15}\).

The integral

\[ \int_0^{x_0} dx' x'^{1/2} \Phi' \]

can be evaluated by integrating the electron density over the whole ion. Suppose that \( r_0 \) defines a sphere centered at the origin of the ion containing a given fraction \((1-\alpha)\) of the Z atomic electrons. Then,

\[ (9) \quad (1-\alpha) = 4\pi \int_0^{r_0} f(r) r^2 dr, \]

where \( f(r) \) is the electron density function given by equation (3).

Therefore, substituting (1) into (9) gives

\[ (10) \quad (1-\alpha) Z = \frac{(4\pi)(8\eta)}{3} \int_0^{r_0} r^2 dr \left[ \frac{2meE}{\Phi(r)} \right]^{3/2}. \]

Using the change of variables given by equations (6) and (7) yields

\[ (11) \quad (1-\alpha) = \int_0^{x_0} dx \times x^{1/2} \Phi' \]

where \((1-\alpha)\) is the average charge of the ion. In the case of the
present experiment, there is no difference between $Z_{av}$ and $Z_{rms}$. Then equation (11) becomes

$$\frac{Z_{rms}}{Z} = \int_{0}^{X_0} dx x \sqrt{\phi^2} \phi^{3/2}.$$  

Finally equation (8) is written as

$$\frac{N_e}{2^{3/2}} = \left[ \left( \frac{1024}{9 \pi^2} \right)^{1/3} \frac{1}{T} \right]^{1/2} \left( \frac{Z_{rms}}{Z} \right)^{1/2}$$
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16. J.C. Legg and Mary Ann Crosby, private communication.
PART II. A Study of the $^{12}\text{C}(\text{He}^3,\text{n})^{14}\text{N}$ Reaction by Pulsed-Beam Neutron Time-of-Flight Techniques.
A. INTRODUCTION

Neutron velocity determination as a measure of neutron energy has had a broad range of applicability. Among the earliest studies of neutron energies by direct measurement of neutron velocities were those concerned with mechanical choppers\(^1\). This method of energy measurement was initially used to measure the energies of neutrons only in the ev range because of the relatively slow action of the device. As better metallic alloys were developed, measurement of neutron energies by these velocity selectors was extended to the kilovolt energy range\(^2\). On account of the development of fast, efficient neutron detectors, the measurement of neutron energy by direct determination of neutron velocity is being extended into the Mev range of energies.

Published work concerned with neutron time-of-flight techniques using instrumental methods applicable to neutrons having 2 Kev or more energy has been limited mainly to cyclotrons and d. c. linear accelerators such as Van de Graaff and Cockcroft-Walton accelerators. Time scales have been reduced to the millimicrosecond range.

The problem of measuring such short time intervals requires the use of fast, accurate electronics. The method used in this experiment involves the production of ion-beam bursts so that neutron burst duration, neutron burst repetition rate, and neutron flux are determined by the quality of the accelerator beam. There are several means of producing bursts of ions in the Mev energy range: (a) beam chopping, (b) plasma pulsing, (c) ion beam bunching, and (d) a combination of (a) and (c).
In practice, (a) has been the method most commonly used and is the method used in the present experiment. Chopping a beam electronically by using a set of deflector plates with an R.F. voltage to sweep the beam of ions across an aperture is the first step necessary to achieve clean ion-bursts, especially when the chopper is located in the accelerator terminal. This method is sometimes referred to as "oscilloscope sweeping."

There are many factors which determine the burst length or burst duration. With the chopper located in the accelerator terminal, the ion-burst length becomes a function of (a) the velocity of the ions moving between the deflector plates, (b) the deflector plate length and separation, (c) the distance from deflector plates to the aperture, (d) the dimension of the aperture along the sweeping direction, (e) the magnitude of the voltage on the deflectors, and (f) the repetition rate of the deflector voltage. For a given experiment, all these factors are usually kept constant. Since the kinetic energy given to the ion bursts by the accelerator for the case of terminal chopping does not effect the ion-burst length, ion-burst repetition rate, and peak current, one, therefore, has a versatile tool for studying neutron producing reactions.

Neutron spectra obtained with a pulsed-beam time-of-flight spectrometer exhibit important advantages because of the facility with which the neutron groups are distinguished from background neutrons of either higher or lower energy. This technique has superiority over such an instrument as the long counter which is sensitive
to low and high energy background neutrons. Whereas most other neutron detection techniques are limited to detecting just a few neutron groups from neutron producing reactions, the pulsed-beam, time-of-flight method is limited in this respect only by its neutron energy resolution of only a few percent. The pulsed beam technique enables one to observe neutron groups to the ground state of the residual nucleus which could not be seen with the associated particle (or gamma ray) time-of-flight techniques.

A reaction lending itself most favorably to be studied with such a neutron spectrometer and with the bombarding energies available from the pulsed 6 Mev Rice University Van de Graaff accelerator is the \( ^{12}\text{C}(\text{He}^3,\text{n})^0\text{A} \) reaction. With bombarding energies below 6 Mev, only the \( 0^1\text{A} \) ground state neutron group is present. It is believed that at sufficiently high bombarding energies, \( (\text{He}^3,\text{n}) \) reactions may proceed primarily by a mechanism similar to that by which \( (\text{d},\text{p}) \) and \( (\text{d},\text{n}) \) reactions proceed.

H.C. Newns\(^3\) has shown by his theoretical treatment of the double-stripping process that \( (\text{He}^3,\text{n}) \) reactions may possess unusually severe selection rules if indeed these reactions proceed by a double-stripping mechanism. In this respect, the \( (\text{He}^3,\text{n}) \) reaction may become a useful tool for nuclear spectroscopic studies.

Previous work reported on the \( ^{12}\text{C}(\text{He}^3,\text{n})^0\text{A} \) reaction includes the work of Bromley et al.\(^4\) who have measured the excitation function in the \text{He}^3 energy range of 1.3 to 3.75 Mev. These workers have made a measurement of the ground state threshold energy as well as angular
distributions of the neutron group to the $^0_{14}$ ground state at bombarding energies of 1.89, 2.16, 2.40 and 2.51 Mev. A BF$_3$ long counter was used for these measurements.

Gale et al.\textsuperscript{5) have measured the angular distributions of the neutron group to the ground state of $^0_{14}$ for bombarding energies of 4.09, 4.62, 5.16 and 5.70 Mev using a post-acceleration pulsed beam time-of-flight neutron spectrometer.

Towle and Macefield\textsuperscript{6) measured angular distributions for He$_3$ energies of 5.3 and 5.5 Mev between 0$^\circ$ and 140$^\circ$ using a long counter. They also measured excitation functions at 0$^\circ$ and 90$^\circ$ for He$_3$ energies up to 5.5 Mev.

Fulbright et al.\textsuperscript{7) compared angular distributions of the C$_{12}^1$(He$_3^3$,n)$^0_{14}$ and C$_{12}^1$(He$_3^3$,p)$^N_{14}$ reactions in the energy range of 6.5 to 10.5 Mev using time-of-flight methods associated with a natural pulsed cyclotron. These workers also measured simultaneous excitation functions of the two reactions at 10$^\circ$ in the energy range 6.5 to 11.2 Mev.

In the present experiment, angular distributions were measured between 0$^\circ$ and 80$^\circ$ at every 200 Kev energy step from 2.00 to 4.6 Mev using terminal-pulsed-beam, time-of-flight techniques. Excitation functions were extracted from these angular distributions at angles of 0$^\circ$, 10$^\circ$, 20$^\circ$, 30$^\circ$, 40$^\circ$, 60$^\circ$, and 80$^\circ$. The interest was to investigate to what extent is the direct-interaction mode of reaction prevalent as a function of bombarding energy as compared to the compound nucleus mode. The direct-interaction mechanism should manifest
itself in peaking of the angular distributions at forward angles, if it exists. Compound nucleus formation would be expected to be shown by rapidly changing angular distributions as a function of bombarding energy. Also, excitation curves should show resonances corresponding to levels in the compound system.
B. EXPERIMENTAL METHOD

1. Arrangement of the apparatus.

The apparatus was arranged as illustrated in the schematic diagram of Figure II-1. The R.F. pulser was located in the terminal of the 6 Mev Van de Graaff accelerator. The output of the pulser was capacitively coupled to the deflector plates of the terminal. The pulsed beam of singly ionized He$^3$ ions was analyzed by a 90° magnet whose field was determined by an NMR probe. After the pulsed beam was directed into the target beam tube, it was focused further by means of an electrostatic quadrupole lens.

The pulsed beam then entered along the long axis of a thin walled brass cylinder from which a signal for triggering the time-of-flight electronics was obtained. The target was located in a small cavity about 6 inches from the target end of the pulse pickoff cylinder. The target cavity was also insulated from the beam tube and functioned as a Faraday cup for beam integration purposes. The cavity was arranged with a shaft along its vertical axis on which the target was fixed. A quartz plate was also fixed to this shaft and located below the target so that the pulsed beam could be observed by raising the shaft and looking through a viewing port on the side of the cavity. The beam could then be kept focused when the He$^3$ bombarding energy was changed.

A viewing quartz was located immediately in front of the pulse pickoff cylinder to provide a means of determining the size of the beam entering cylinder. The beam spot seen there was kept smaller
Figure II-1. Schematic diagram of the arrangement of the pulsed-beam time-of-flight apparatus.

Legend:

A. Terminal pulser
B. Accelerator
C. Electrostatic pulse pickup cylinder
D. LiCO₃-paraffin shield
E. 2 mm. lead shield for gamma rays
F. 1/4 inch lead lining
G. Plastic scintillator, 1.75" dia. x 2" long
H. 56AVP photomultiplier tube
I. H.T. power supply
J. Cathode follower
K. Single channel analyzer
L. Slow coincidence unit
M. Time-pickoff and fan-out unit
N. Oscilloscope
O. 250 nanosecond delay
P. Time-pulse height converter
Q. Fast amplifier
R. 10 megacycles scaler
S. 256-channel analyzer
T. Linear amplifier
U. Carbon-12 target
in diameter than the inside diameter of the pulse pickoff cylinder so that no part of the cylinder was struck by the pulsed beam.

The neutron detector was positioned at 1 meter or 1.5 meters from the target depending on the experimental conditions encountered during the experiment. The neutron detector was shielded from neutrons not originating directly from the target by a lithium carbonate loaded paraffin shield. The detector and shield assembly rode on an aluminum frame on casters which provided easy mobility for the detector when taking angular distributions. The solid angle subtended by the neutron detector was $1.55 \times 10^{-3}$ steradian when positioned at 1 meter from the target and $6.90 \times 10^{-4}$ steradian at 1.5 meter from the target.
2. The terminal pulser.

Figure II-2 shows a schematic diagram of the arrangement of the electrical components of the R.F. pulser. A standard crystal controlled oscillator utilizing a 5763 pentode vacuum tube is broadly tuned by a plate tank circuit. The plate of the 5763 is capacitively coupled to the grid of a 25T power amplifier tube. The grid of the 25T was driven with a 100 to 200 volt swing. Since the gain of the 25T is about 10, one should be able to obtain 1000 to 2000 volts (peak-to-peak) sinusoidal oscillations from the output of such a circuit. For this experiment the R.F. level used was 1400 volts. The plate of the 25T was capacitively tuned with the terminal deflector plates as part of the tank circuit of the output stage of the pulser.

The terminal deflector plates are about 2 1/2 inches long and the center of the plates is about 9 inches from the 1/8 inch aperture at the entrance of the accelerator tube of the Van de Graaff. With this geometry and with an ion extraction voltage between 1 and 2 kilovolts at the ion bottle, one could obtain 10 nanosecond burst lengths with the 1400 volts of R.F. level oscillations of the pulser. Since no provisions were made in the terminal to eliminate the retrace of the beam across the upper accelerator tube aperture, the trace and retrace beams were accelerated by the Van de Graaff. The pulser frequency was 2.5 megacycles per second, thus giving an ion-burst repetition rate of 200 nanosecond. The horizontal sweep of the beam across the upper aperture gave a small horizontal component of momentum to the trace and retrace bursts in opposite directions. By the time the
Figure II-2.
Schematic diagram of the pulser electronics.
bursts reached a quartz viewer just above the 90° analyzing magnet, there existed a clear separation of the trace and retrace pulsed beams. The separation of the two beams was such that the beam splitter magnet, located just above the 90° analyzing magnet, was used to displace the beams such that only the trace pulsed beam was permitted to be analyzed by the 90° magnet. This beam, then, had a repetition rate of 400 nano-seconds.
3. The time-of-flight electronics.

The pulsed beam of He$^{3}$ ions, after being analyzed by the 90° magnet and properly focused by an electrostatic quadrupole lens was allowed to enter the hollow brass pulse pickoff cylinder along its long axis. The cylinder was 5/8 inch in diameter and 6 inches long with a 1/16 inch thick wall. It was insulated from the beam tube by Teflon spacers. Figure II-1 illustrates schematically the arrangement of the pulsed beam time-of-flight electronics. A 50 ohm electrical connector was soldered directly on the cylinder. The connector was of special design to permit its use as an electrical outlet from a vacuum system. Pulses obtained from this device were fed by means of a 50 ohm coaxial cable to a transformer-coupled pulse amplifier and shaper which required a minimum input voltage of about 10 microvolts. The pulses from this amplifier were then fed to the stop side of a time-to-pulse height converter after being delayed by about 250 nanoseconds.

One of the many features of the converter was that its stop input was able to accept faster repetitive rates than could be accepted in the start input. For example, its maximum stop input counting rate was $5 \times 10^6$ pulses per second compared to $5 \times 10^4$ pulses per second for the start input. For this reason, the 2.5 megacycles per second pulses from the electrostatic pickup cylinder were fed to the stop input of the converter. The stop signals were monitored by a fast scaler and an oscilloscope.
The neutron detector initiated the start pulses for the converter. A schematic diagram of the special coupling of the scintillator is shown in Figure II-3. A 1.75 inch diameter by 2 inch long plastic scintillator was permanently mounted in a thin walled (1/32 inch thick) aluminum can. Before mounting the scintillator in the can, the inside of the can was smoked by burning magnesium metal strips near the opening. The polished scintillator was then placed in the smoked container and a Pyrex glass window 1.75 inches in diameter by 1/8 inch thick was joined to the scintillator by an optical coupling fluid. The glass window permitted the plastic scintillator to be fastened in place since a strong resin adhesive could be used to glue the periphery of the glass window to the aluminum can. This scintillator assembly was then mounted on a cylindrical aluminum housing with a 1/16 inch thick wall containing a 56AVP, 14 stage photomultiplier tube and tube base. The scintillator can fitted onto an "O" ring around the photo-cathode end of the photomultiplier tube and made the 1/8 inch gap between the end of the photomultiplier tube and the glass window air tight. The air in the gap could then be evacuated and a mineral oil was bled in as an optical coupling fluid between the scintillator and the photo-cathode surface. The anode signal out of the tube base was used as the input signal to a second transformer-coupled amplifier and shaper preceding the start input of the time-to-pulse height converter as illustrated in Figure II-1.

The signal from the twelfth dynode of the 56AVP photomultiplier tube was used for setting the bias requirement of the detector. The
Figure II-3. Schematic diagram illustrating the neutron detector mount incorporating a plastic scintillator with a 56AVP photomultiplier tube. This provided a durable, strong coupling of the plastic scintillator to the photomultiplier tube free of air bubbles.
dynode signal was fed to a cathode follower. The pulses from the
cathode follower were amplified and fed to a single channel analyzer.
The constant 4 volt (positive) pulse out of the single channel ana-
lyzer was used as one input signal of a slow coincidence circuit.
The other input of the slow coincidence unit received amplified out-
put pulses from the time-to-pulse height converter which had already
gone through a single channel requirement to eliminate converter out-
put pulses due to input start pulses with no corresponding stop
pulses. The output pulses of the slow coincidence unit were used to
gate the 256-channel analyzer which analyzed pulses from the converter.

There were two base line or pulse height discriminator controls
associated with the neutron detector. One of these controls was
incorporated with the transformer-coupled amplifier and pulse shaper
which accepted pulses directly from the anode of the photomultiplier
tube and fed these shaped pulses to the start side of the converter.
Another pulse height discrimination was made by the single channel
analyzer which analyzed pulses from the twelfth dynode of the photo-
multiplier tube. In setting these two base line discriminators, care
had to be taken so that the base line setting for the anode signal
was lower than that for the dynode signal, otherwise the side channel
circuitry would have been useless in placing a detector bias require-
ment on the data accumulated.

First, the side channel discriminator had to be adjusted to some
value. Since low energy neutrons were to be detected in the experiment,
the side channel bias had to be set to a value as low as possible. The
minimum setting was limited only by the photomultiplier tube noise.
The output of the linear amplifier of the side channel preceding the single channel analyzer was fed to a multichannel analyzer. The multichannel analyzer was then gated by the output of the single channel analyzer. A Na$^{22}$ radioactive source was placed near the detector and a gated spectrum of the 511 Kev annihilation radiation from the source was recorded by the multichannel analyzer. The base line control of the single channel analyzer was then varied until pulses due to photomultiplier tube noise were cut off. This lower pulse height setting corresponded to $1/9$ (or 11 percent) the pulse height due to the 511 Kev annihilation gamma rays from Na$^{22}$ being Compton scattered from the plastic scintillator. This side channel base line setting defined the detector bias and was fixed throughout the experiment. Thus, the output of the side channel analyzer was used to gate the multichannel analyzer when analyzing data. This method of setting the detector bias could be accurately reproduced at any time.

The next step was to adjust the discriminator for the anode signal. To do this, use was made of the characteristic of the converter by which it gives an output pulse whenever there is an input start pulse but no corresponding input stop pulse. Again using a gamma ray source, the pulses out of the converter and out of the dynode single channel analyzer were fed to scalers. Then the anode discriminator level was lowered until the counting rate out of the converter was higher than that out of the single channel analyzer, but still rejecting photomultiplier tube noise.
The discriminator level of the transformer-coupled amplifier and pulse shaper, which accepted pulses from the electrostatic pulse pickup cylinder, was also adjusted such that when the pulsed beam was turned off the discriminator level was set just above the noise level.

The single channel analyzers used in this experiment had baseline and window width controls. In use in the photomultiplier dynode side channel, the window width of the single channel analyzer was set at its maximum setting, allowing analysis of a maximum of 10 volt input pulses. The baseline of the side channel analyzer was set, as discussed above, such that no pulses were analyzed whose pulse height was below 1/9 the pulse height due to the 511 KeV annihilation gamma rays from a $^{22}$Na source Compton scattered from the plastic scintillator. The single channel analyzer used with the converter output pulses had its baseline at zero and its window width set such that the output pulses from the converter due to a start pulse with no corresponding stop pulse were partially cut off. This reduced large counting rates into the multichannel analyzer to reasonable rates when the actual data was being accumulated.
4. The target.

Carbon foils were obtained by cracking methyl iodide on strips of tantalum metal using the same method described elsewhere \(^8\). A self-supporting carbon foil obtained by this technique was then sandwiched between an aluminum ring and a 5 mil thick tungsten backing. This assembly provided a 1.5 square centimeter area of carbon foil which could be exposed to the beam and provided a means of stopping the \(\text{He}^3\) beam into a backing which did not give appreciable radiation for the bombarding energy range used. The target and backing assembly was then mounted on the positioning rod of the scattering cavity.

Portions of the target foil not used as the target for this experiment were weighed with a micro balance. The area of the foils were measured and the thickness of the carbon was found to be 580 \(\mu\text{gm/cm}^2\) with an accuracy of about 2 percent. This corresponded to about 500 Kev energy loss for 2 Mev \(\text{He}^3\) bombarding particles.
5. Detector efficiency.

Before taking data with any neutron detector, either the relative efficiency or the absolute efficiency of the detector, depending upon the experiment to be performed, must be calculated for the range of neutron energies to be investigated. Such calculations were made during this experiment and the results are shown in Figure II-4 as a graph of relative efficiency versus neutron energy. The output of the side channel analyzer, which analyzed the linear pulses from the twelfth synode of the neutron detector and which set the detector bias requirement on these pulses, was fed to a scaler. The output of a BF$_3$ long counter, set at the same angle, about 37° with respect to the incident beam direction, was also fed to a scaler. With this arrangement the excitation yield of the T(p,n)He$^3$ reaction was measured and the ratio of neutron detector counts to neutron monitor (BF$_3$ long counter) counts for a given beam charge accumulated was plotted as a function of neutron energy. The discriminator of the long counter amplifier was set such that gamma rays from a Co$^{60}$ source were not detected. This was done before the above measurements were made and was sporadically checked during the course of the experiment with the C$^{12}$ (He$^3$,n)$^{14}$ reaction.

Thus, the graph of Figure II-4 shows the neutron detector relative efficiency curve for the detector bias set for rejecting all pulses lower than those corresponding to 11 percent of the pulse height due to the 511 Kev Na$^{22}$ annihilation gamma rays. The lowest neutron energy detected by this system was found by extrapolating the efficiency curve to zero efficiency.
Figure II-4. A plot of the relative neutron detection efficiency of a 1.75 inch diameter by 2 inch long plastic scintillator mounted on a 56AVP photomultiplier tube. The maximum relative efficiency illustrated by this curve corresponds to 40 percent absolute efficiency.
Relative Efficiency vs. Energy
The detection of gamma rays and the detection of neutrons by a plastic scintillator occur by different mechanisms. Gamma rays interact with the electrons in the scintillator such that for gamma rays of a few hundred kilovolts of energy and more, interaction with the plastic scintillator of the size used in this experiment occurs strictly by Compton scattering. Thus, the gamma ray energy deposited in the scintillator is given to a recoiling electron. Neutrons, on the other hand, interact with the hydrogen and carbon nuclei in the scintillator—mostly with hydrogen nuclei for the neutron energies investigated in this experiment. Thus, the neutron energy deposited in the plastic scintillator is given to recoil protons. Consequently, there is no simple relationship between the energies deposited in the scintillator by a gamma ray and a neutron of the same energy. However, one may note from the efficiency curve of Figure II-4 that since the Compton edge of a 511 Kev gamma ray corresponds to about 350 Kev, one can surmise that the pulse height from the plastic scintillator due to detection of 300 Kev neutrons is the same as that corresponding to 39 Kev (or 1/9 x 350 Kev) gamma rays.

Since the Van de Graaff accelerator could not be operated reliably below 1.5 million volts on the terminal, the lowest energy of neutrons produced by the T(p,n)He\(^3\) reaction was about 600 Kev. The position of the point on the curve corresponding to the lowest neutron energy detected shows the expected drop in the relative efficiency curve. However, the amount of curvature of that portion of the curve cannot be accurately determined, so that the uncertainty in the extrapolated 300 Kev neutron energy bias is about ± 20 percent.
The BF$_3$ long counter was calibrated with a plutonium-beryllium source of known source strength. From this calibration procedure, the counts recorded by the long counter were expressed as a function of source strength and the distance between the source and the effective center of the long counter. The expression obtained was

\[
\text{counts} = \frac{(0.269)xS_n}{(d+r_o^2)},
\]

where $S_n$ is the neutron source strength, $d$ is the distance from the source to the front face of the counter and $r_o$ (=14 cm) is the effective half length of the counter. In obtaining this expression, the response of the long counter to neutrons from the plutonium-beryllium source was assumed to be flat. This could introduce an error in neutron flux determination of about $\pm$ 5 percent, at most. The response of a long counter to neutron energies between a few kilvolts to about 9 Mev is fairly flat except at the regions of the carbon resonances.$^{12}$

A similar expression was obtained for the biased neutron detector so that by comparing the counting rate of the neutron detector with that of the long counter while measuring the neutron flux from the same source of monoenergetic neutrons, the absolute efficiency of the neutron detector could be determined. The maximum absolute efficiency was found to be 40 percent for the detector bias used.

In determining the absolute efficiency of the neutron detector by using the graph of Figure II-4, an upper limit to the error of the readings is placed at $\pm$ 10 percent.
C. DISCUSSION OF RESULTS

1. Observations.

The $^{12}\text{C}(\text{He}^3,n)^{14}\text{O}$ reaction has a Q-value of $-1.148$ Mev. The first excited state of $^{14}\text{O}$ is at $5.91$ Mev, thus allowing only the emission of neutrons to the ground state of $^{14}\text{O}$ for the range of bombarding energies reported here. The neutron threshold energy is $1.449$ Mev$^{13}$. A schematic diagram of the energy levels and their spin and parity is shown by Figure II-5.

Figure II-6 shows a typical neutron time-of-flight spectrum of the neutron group from the $^{12}\text{C}(\text{He}^3,n)^{14}\text{O}$ reaction obtained with the apparatus schematically illustrated in Figure II-1. The flight path for this particular spectrum was $1.5$ meters. The $\text{He}^3$ energy after correcting for energy loss in the target, was $4.20$ Mev giving neutrons of energy $2.80$ Mev at $10^\circ$ in the laboratory coordinates. The peak on the extreme right end of the spectrum is due to pulses from the converter caused by input start pulses with no corresponding input stop pulse. Even though a window was set on the converter pulses to reduce the counting rate of these instrument pulses, a few were permitted to be analyzed in order to explicitly show the end of the converter time range. The second and most intense peak is identified as due to gamma rays from the target. The third peak from the right hand side is the neutron group to the ground state of $^{14}\text{O}$. A 256-channel analyzer was used to analyze the data taken in this experiment. The time calibration at $1.5$ meter flight path was $1.00$ nanosecond per channel for a converter time range of $250$ nanoseconds.
Figure II-5. Energy level diagram of the $^{14}\text{O}$ nucleus.
Figure II-6. A typical neutron time-of-flight spectrum taken with the pulsed He$^3$ beam and associated time-of-flight apparatus described in the text. The bombarding energy is 4.21 Mev (corrected for target energy loss) and the neutron detector was located at 10°. The flight path was 1.5 meters and the time calibration was 1.00 nanosecond per channel. The zero-time channel is at channel 200. Thus, the neutron time of flight is about 64 nanoseconds.
Not all of spectra were taken at flight paths of 1.5 meters. At lower bombarding energies, from 2 to 3.4 Mev, the flight path was 1 meter and the time calibration was 0.88 nanoseconds per channel. The combined time resolution due to ion-burst length and electronic time resolution is obtained from the FWHM of the gamma ray peak. This corresponds to about 12 nanoseconds for this example. The neutron time resolution is obtained from the FWHM of the neutron peak. The FWHM of the neutron peak contains time resolution contributions mainly from (a) ion-burst length, (b) target thickness, (c) thickness of the scintillator and (d) time-of-flight electronics. The largest contributors are (a) and (b). The ion source had to be retuned during the performance of the experiment so that the total time resolution did not vary strictly as a function of neutron energy but also involved an added effect due to increase or decrease of ion-burst length. Since the spectrum illustrated in Figure II-6 represents a typical example, the neutron time resolution was calculated for this case and was found to be 13 nanoseconds which corresponds to about 1 Mev neutron energy resolution. A sacrifice of time (or energy) resolution was allowed in this experiment because only one neutron group was being investigated. Furthermore, by comparing the FWHM's of the gamma ray and neutron peaks, the ion-burst length is by far the largest contributor to the energy resolution of the neutron peak. This was the general case throughout the experiment. Spectra of this type were taken at 0°, 10°, 20°, 30°, 40°, 60° and 80° in the laboratory coordinates for bombarding energies ranging from 2.00 to 4.70 Mev in energy steps of
about 200 Kev. This corresponds to an excitation in the $^{15}$ compound
nucleus of 13 to 16 Mev.

The angular distributions were plotted in the center of mass
system and have an error in the absolute measurement of $\pm$ 12 percent.
The relative error is $\pm$ 3 percent. Excitation functions were extracted
from the angular distributions and plotted in the laboratory system.

Figures II-7 - II-9 show angular distributions for forward angles
as differential cross section versus angle in the center of mass sys-
tem for $^{\text{He}}^3$ bombarding energies of 1.97, 2.29 and 2.50 Mev. The curves
drawn are just lines through the points. At 2.50 Mev the angular
distribution begins to show a marked peaking at small angles, but also
shows a slight dip at 0°, indicative of compound nucleus level inter-
ferences. These angular distributions compare qualitatively with
those of Din et al.\textsuperscript{14} although they were measured at a slightly dif-
fferent bombarding energy. The present angular distributions show more
structure than those of Din because of better angular resolution ($\pm 1°$).

From 2.7 to 3.8 Mev $^{\text{He}}^3$ energies, 0° peaking of the angular dis-
tributions continue as illustrated by Figures II-10 - II-15. The
maximum cross section occurs at 0° in all cases with the case for
2.93 Mev having the largest cross section of 3.0 millibarns per
steradian. There is some disagreement of the absolute measurements
between the 2.93 Mev angular distribution and that of Din at 2.78 Mev
at 0° although Din's error in the absolute measurements is $\pm$ 50 percent.

Figures II-16 - II-19 illustrate the angular distributions for
4.00, 4.21, 4.43 and 4.70 Mev bombarding energies. These distributions
show a striking increase in differential cross section with an increase
Figures II-7 - II-15. Angular distributions of the $^{12}\text{C} \left(\text{He}^3,\text{n}\right) ^{14}\text{O}$ reaction in the center of mass system for forward angles for the bombarding energies of 1.97 to 3.57 Mev. The curves drawn are lines through the data points. The error in the absolute measurements is $\pm 12$ percent and in the relative measurements, $\pm 3$ percent. The angular resolution is $\pm 1^\circ$. 
Figures II-16 - II-19. Angular distributions of the $^{12}\text{C}(\text{He}^3,\text{n})^{14}\text{N}$ reaction in the center of mass system for angles for the bombarding energies of 3.79, 4.00, 4.21, 4.43 and 4.70 Mev. Note the increasing manifestation of $0^\circ$ peaking. The error in the absolute measurements is $\pm$ 12 percent and in the relative measurements, $\pm$ 3 percent. The angular resolution is $\pm$ 1$^\circ$. 
in bombarding energy. Furthermore, 0° peaking becomes more manifest in going from 4.00 Mev to 4.70 Mev. The 4.00 and 4.70 Mev angular distributions agree quite well with the forward angle measurements of Gale et al.\(^5\) at 4.09 and 4.62 Mev and with Din et al.\(^{14}\) at 4.75 Mev. The 4.43 Mev angular distribution also agrees with Din's forward angle measurements at 4.49 Mev.

Figure II-20 shows an isometric display of the data. Angular distributions for forward angles only are displayed as a function of bombarding energy. Increasing contributions of direct-interaction with increasing energy is clearly seen in this display. Nevertheless, fluctuations in the distributions with energy suggests interference of levels in the compound nucleus.

The excitation curves obtained from the angular distributions are shown in Figures II-21 - II-27. The laboratory differential cross section is calculated and plotted for laboratory angles of 0°, 10°, 20°, 30°, 40°, 60° and 80° and for a bombarding energy range of 1.97 Mev to 4.70 Mev. The curves drawn through the points are not fits to the data but only lines through the data points. Two resonances are seen between 2.4 and 3.2 Mev bombarding energies. The energy position of these resonances does not change as a function of laboratory angle; however, their relative amplitudes fluctuate. The resonances become better resolved at 30°. More structure is seen between 3.30 and 4.70 Mev than has been observed before by a different method\(^6\),\(^{14}\). At 60° and 80°, a broad resonance is showing at about 4.2 Mev. In going from 60° to 80°, this resonance decreases in cross section but becomes better resolved.
Figure II-20.
An isometric display of the angular distributions as a function of bombarding energy.
Excitation curves extracted from the angular distributions illustrating the yield fluctuating as a function of energy—a characteristic of compound nucleus effects. The curves shown are lines drawn through the data points.
2. Theory.

Works in the past \textsuperscript{7,9} have compared data from the reactions $C^{12}(\text{He}^3, p)N^{14}$, $C^{12}(\text{He}^3, n)O^{14}$ and $C^{12}(t, p)C^{14}$ to determine to what extent these reactions are similar insofar as the direct-interaction and compound nuclear theories, or combinations of both, are concerned. These reactions lead to states which are members of an isobaric spin triplet, i.e., the ground states of $O^{14}$ and $C^{14}$, and the 2.3 Mev first excited state of $N^{14}$ have total isobaric spins of $T = 1$.

The $C^{12}(\text{He}^3, n)O^{14}$ and $C^{12}(\text{He}^3, p)N^{14}$ reactions involve $0^+ \rightarrow 0^+$ transitions. Thus, one should expect contributions to the reaction cross section coming from the transfer of two nucleon clusters with zero intrinsic spin and zero orbital angular momentum.

Direct-interaction modes of reactions, such as in $(d, n)$ and $(d, p)$ reactions, have received much attention and achieved much success in deuteron stripping theories \textsuperscript{10}. Lately the same general ideas have been included in applications to such reactions as $(\text{He}^3, n)$, $(\text{He}^3, p)$ and others involving double stripping processes as well as inverse, or pickup, processes. Direct-interaction theory predicts angular distributions peaked at small angles and having weaker secondary maxima at larger angles. The simplest calculations of double-stripping theory are those of Newn's \textsuperscript{3} from which the reaction cross section in the center of mass system of coordinates can be written from plane wave considerations as
\[ \frac{d\sigma}{d\Omega} = \text{Constant} \cdot \frac{1}{\mu} ( -K^2/4\gamma^2 ) \left| j_0 ( \kappa r_0 ) \right|^2, \]

where \( \kappa = \kappa_3 - \frac{(M_i)}{M_f} \kappa_n(p) \) is the momentum transferred to the initial nucleus during stripping, \( \kappa = \frac{1}{2} \kappa_3 - \kappa_n(p) \) is the momentum of the outgoing neutron (proton), and \( \gamma \) is a measure of the size of the plane wave function representing the incoming He\(^3\) particle. \( M_i \) and \( M_f \) are the masses of the initial and final nuclei.

Using the above expression for the reaction cross section, the best fits have been obtained for forward angles; however, the fitting is not good at backward angles\(^5\),\(^7\). Furthermore, data accumulated on (He\(^3\),p) reactions show that the yield of the outgoing particles as exemplified by excitation curves is strongly energy dependent while the plane wave direct-interaction theory predicts a slow variation with energy.

As a consequence, other ways of describing the mode of reaction in the (He\(^3\),n) case and similar cases have been investigated. For instance, the compound nucleus mode of reaction has been considered as a competing possibility and, furthermore, a possible interference between the direct-interaction and compound nucleus modes has been suggested in some cases\(^7\).

A qualitative feature of compound nucleus reaction is illustrated in angular distributions which change rapidly with energy. Also, excitation curves, in this case, would show resonances corresponding to levels in the compound system. The asymmetry about 90° of angular distributions in the center of mass coordinates can be
attributed to interference contributions between levels of different parity available in the compound nucleus. Distorted wave Born approximation in direct-interaction theory, which has included effects caused by nuclear scattering and absorption of ingoing and outgoing waves\textsuperscript{11}, has led to better fits with experimental data than does the plane wave direct-interaction theory in predicting a stronger dependence of cross section on energy at backward angles. This seems to be the most promising approach to fitting the data at energies where direct-interaction is predominant.

From the data accumulated to date on \((\text{He}^3,n)\) reactions, in particular the \(\text{C}^{12}(\text{He}^3,n)\text{O}^{14}\) reaction, there appears to be no bombarding energy above which compound nuclear effects can be neglected entirely.
D. CONCLUSION

The angular distributions below about 4.00 Mev show fluctuations in shape and these fluctuations are exhibited in the excitation curves as resonances in the compound nucleus. The agreement with other data above 4.00 Mev which has been analyzed with direct-interaction theory at forward angles is good. The angular distributions presented here do not conform in detail to either compound nucleus or direct-interaction theories. Features of both mechanisms are present. Therefore, analysis of this data from only compound nucleus or only direct-interaction considerations would not be justified.

Finally, even with poor energy resolution, the pulsed-beam time-of-flight technique used here has proven to be a useful tool to study a single neutron group.
BIBLIOGRAPHY, PART II


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